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NEUTRINO OSCILLATION EXPERIMENTS WITH ATMOSPHERIC NEUTRINOS *

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Abstract

The possible atmospheric neutrino deficit is reviewed with an emphasis on recent data. The regions of Δm^2 implied by a neutrino oscillation hypothesis are considered.

1 Introduction

The atmospheric neutrino beam is a mixture of approximately $\frac{1}{3}$ $(\nu_e + \bar{\nu}_e)$ and $\frac{2}{3}$ $(\nu_\mu + \bar{\nu}_\mu)$. It is therefore possible in principle to do both ν_μ and ν_e disappearance and appearance experiments with this beam. Various classes of atmospheric neutrino interactions are defined:

- Fully contained events are those with all tracks inside the fiducial volume of the detector;
- Partially contained events have the vertex inside the fiducial volume but at least one exiting track;
- Upward, stopping neutrino-induced muons are produced outside the detector, but stop inside a fiducial volume;
- Upward, throughgoing neutrino-induced muons pass through the detector having more than some minimum track-length inside a fiducial volume.

When considering the atmospheric neutrinos as a beam for oscillation searches, it is useful to know the distribution of neutrino energies responsible for these classes of interactions. These are shown in Fig. 1. The neutrino energies for most contained events are below threshold for τ-production, making a ν_τ appearance experiment very difficult.

Low statistics limit the reach in $\sin^2\theta$, while E_ν and R_{Earth} limit the reach in δm^2 of neutrino oscillation experiments with the atmospheric neutrino beam. Uncertainties in normalization of the primary cosmic ray beam, together with uncertainties in the production of pions and kaons in proton collisions with light nuclei, translate into significant uncertainties in the normalization and shape of the atmospheric neutrino spectrum at production. For this reason, conclusions based on ratios are the most secure.

In the next four sections we consider the data for the 4 classes of events. Implications for neutrino oscillations are then discussed.

2 Contained Events

The neutrino flavor ratio from experiments which measure contained events is shown in Table 1 while the data and calculations themselves are shown in Table 2. The flavor ratio is

$$R \equiv \frac{\nu_\mu/\nu_e)^{data}}{\nu_\mu/\nu_e)^{MC}} \qquad (1)$$

while the experiments actually measure

$$R' \equiv \frac{track/shower)^{data}}{track/shower)^{MC}} \qquad (2)$$

which only differ if there are neutrino oscillations in the presence of neutral current background to the track and shower samples.

The high statistics water Cerenkov detectors in Table 1 have two ways to distinguish quasi-elastic ν_μ and ν_e events. In one method, the shape of the Cerenkov ring on the wall of the phototubes is used. In the other method, they look for excess phototube hits in a window several microseconds after the event, which would indicate μ or π decay.

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The two methods have different systematic errors, but are statistically correlated. Experimental tests of e/μ detection efficiency are underway at KEK. Results from the Kamioka group presented at Eilat [1] show no sign of misidentification. Results from the IMB exposure at KEK can be expected in a few months. The Frejus experiment prefers to analyze their contained and partially contained events together and this is discussed in the next section.

Experiment	Exposure kT-year	R'
IMB1	3.8	0.68 ± 0.08
Kamiokande ring	7.70	0.60 ± 0.06
Kamiokande decay		0.69 ± 0.06
IMB-3 ring	7.70	0.54 ± 0.05
IMB-3 decay		0.64 ± 0.07
Frejus contained	2.0	0.87 ± 0.13
Soudan	1.01	0.64 ± 0.19
NUSEX	0.5	0.99 ± 0.29

Table 1: The Atmospheric Neutrino Flavor Ratio. Quoted errors are statistical and systematic added in quadrature.

Experiment	TR^{see} (ν_μ^{see})	TR^{MC} (ν_μ^{MC})	SH^{see} (ν_e^{see})	SH^{MC} (ν_e^{MC})
IMB1	104	136	297	265
Kam. ring	234	356.8	248	227.6
Kam. decay	182	277.5	300	313.9
IMB-3 ring	182	268	325	257.3
IMB-3 decay	208	261.5	402	348.5
Frejus contained	94	100	89	82
Soudan	33.5	42.1	35.3	28.7
NUSEX	32	36.8	18	20.5

Table 2: The data on the Atmospheric Neutrino Deficit. TR refers to single tracks, SH to single showers

The results on contained atmospheric neutrino events are consistent with each other if there is a 30-40% deficit of ν_μ events. Such a deficit could be the result of either $\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_e$ oscillations. Since the interpretation of the atmospheric neutrino anomaly in terms of neutrino oscillations depends on the normalization of the neutrino flux, it is desirable to check the normalization as well as possible. In a conventional two-detector neutrino oscillation experiment, this is done by measuring the interaction rate in the neutrino beam close to the source. The nearest analog for the atmospheric neutrino beam of a close-in detector is a measurement of the intensity of muons at the same altitudes where both the neutrinos and muons are produced (10 to 20 km). New, higher precision measurements of this flux are being made [2, 3], and preliminary results [2] are consistent with a relatively high normalization of the neutrino flux [4]. This favors a $\nu_\mu \leftrightarrow \nu_\tau$ interpretation of the atmospheric neutrino puzzle.

3 Partially contained events

The most recent new result on atmospheric neutrinos was presented during the Snowmass meeting [5]. This was the Kamiokande analysis of their "multi-GeV" events, which include fully contained events with $E_{\rm vis} > 1.33$ GeV as well as partially contained events. The mean neutrino energy responsible for this class of events is ~ 6 GeV, as shown in Fig. 1. This is nearly an order of magnitude higher than for the independent sample [6] of contained events with $E_{\rm vis} < 1.33$ GeV. In this new data sample, there is again evidence for a ν_μ deficit, with a measurement of $R' = 0.59 \pm 0.08$.

The most remarkable feature of the data is the appearance of an angular dependence of the muons of the kind that would be expected if downward muons have path-lengths too short to oscillate; that is, the upward muons are suppressed relative to the downward muons. Given the range of E_ν and R involved for the multi-GeV sample, Eq. 3 below implies an upper limit on δm^2. In contrast to the muons, the angular dependence of the electrons is closer to what is expected if the ν_e are not affected by oscillations. The angular-dependence alone therefore suggests an interpretation in terms of ν_μ disappearance.

On the other hand, a preliminary re-analysis of the Frejus data presented at Snowmass [7] seems to be even more divergent from the results of Refs. [6, 8] than the original Frejus publication [9]. A simultaneous analysis of their contained, partially contained, and throughgoing muons leads to a neutrino oscillation exclusion plot which contradicts a neutrino oscillation interpretation of the data in Table's 1 and 2. It is seen that by itself, the Frejus fully contained data is not in strong disagreement with the other experiments. However, their partially contained events and neutrino induced throughgoing muons seem to be in conflict with the new Kamiokande result. An analysis of all Frejus

neutrino data leads to the result $R = 0.96 \pm 0.18$.

One puzzling feature of the new Kamiokande result is that there appears to be a large excess of electron neutrinos and a relatively small deficit of muon neutrinos as compared to the calculation. Using the neutrino flux of Ref. [10], they find

$$e - \text{like} \left(\frac{\text{measured}}{\text{calculated}}\right) = 1.47$$

and

$$\mu - \text{like} \left(\frac{\text{measured}}{\text{calculated}}\right) = 0.83.$$

The corresponding numbers for the low-energy, fully contained event sample are 1.09 (electrons) and 0.66 (muons). Thus, while the low energy sample suggests $\nu_\mu \leftrightarrow \nu_\tau$, the high energy sample looks more like $\nu_\mu \leftrightarrow \nu_e$. However, the ν_e excess may be just a statistical fluctuation.

We also note a statistical point regarding Kamiokande's angular dependence. They plot R = $(\nu_\mu/\nu_e)^{data}/(\nu_\mu/\nu_e)^{MC}$ versus zenith angle. Part of that ratio, ν_e^{data}/ν_e^{MC} is for flux normalizaiton only, and should be flat within statistics in both the no-oscillation case and the $\nu_\mu \rightarrow \nu_\tau$ hypothesis. Binning the ν_e data adds statistical fluctuations to the angular dependence plot which contribute no information. A better representation is $(\nu_\mu/ < \nu_e >)^{data}/(\nu_\mu/\nu_e)^{MC}$ where the ν_e average is over all angular bins. If this is done, there is still evidence for an angular distribution due to oscillations, but from a mixing angle which is not maximally mixed.

4 Upward stopping Muons

The measured ratio of stopping to throughgoing upward neutrino-induced muons is consistent with expectation [11]. The data is shown in Table 3. This means *either* that there are no oscillations of ν_μ with mixing angle and δm^2 large enough to be seen with upward neutrinos *or* that there is large mixing of ν_μ, but with δm^2 large enough so that the lower energy stopping muons as well as the higher energy throughgoing muons are affected. The measured stopping/throughgoing ratio is used to rule out a range of $10^{-3} < \delta m^2 < 10^{-2}$ eV^2 at large mixing angle for ν_μ disappearance [11].

The ratio of upward stopping muons to throughgoing muons is sensitive to the absence of background from events which are not initiated by neutrinos. In particular, downgoing muons which initiate hadronic cascades in the rock could mimic upward going stopping muons in some cases. There is evidence for such events from Soudan, Kamioka, and MACRO[12, 13, 14], but it is not straightforward to calculate the possible contamination of the IMB data sample. We do note, however that a background of 12 events out of the 85 would lead to the absence of any neutrino oscillation limit from the IMB analysis, and also that the comparison of upward showers to expectation in IMB may be evidence that such a background in fact exists.

	Observed	Calculated
Stopping tracks	85	84
Exiting tracks	532	516
Showers	49	17

Table 3: Neutrino induced upward event rates in IMB.

5 Upward Muons

Because the implication of upward muon measurements have been somewhat controversial, it is worth going into a little more detail. The IMB group [11] calculated the rate of upward, throughgoing muons starting from a particular neutrino flux [15] and a particular representation of the neutrino cross section [16]. Their calculated rate agreed with their measured rate, apparently ruling out most of the available parameter space needed for a $\nu_\mu \leftrightarrow \nu_\tau$ interpretation of the low energy, contained event anomaly. Frati et al. [17] showed that the Kamiokande data on upward, throughgoing muons [18] is similarly consistent with a calculation assuming the same input. On the other hand, they found that, starting from different, more recent calculations of the neutrino flux [19, 20] and a different representation of the cross section [21], the predicted rate is some 15% higher than the observed rate. They further showed that a discrepancy of this size is consistent with a range of parameters needed to explain the contained event anomaly as $\nu_\mu \leftrightarrow \nu_\tau$. Recently reported results from MACRO [22] similarly show a significant deficit of the measured upward rate as compared to a calculation with the "high" input assumptions. This matrix of measurements and calculations is indirect evidence that these experiments and calculations are all consistent with each other. The same cannot be said for Baksan [23] where there is agreement

between measurement and expectation for "high" input assumptions, but an *excess* of measurements over calculation when the low input is used. In all cases the differences are only of marginal statistical significance, as indicated by the summary of measurements/calculations in Table 4.

Experiment	Observed	Calculated "high"	"low"
IMB [11]	0.47 ± 0.02	—	0.455
KAM [18]	2.04 ± 0.13	2.36	2.18
Baksan [23]	161	162	142
MACRO [22]	$74 \pm 9 \pm 8$	101 ± 15	—

Table 4: Upward muons. For Kamioka the units are upward muons in units of $10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. For IMB, upward events per day and for Baksan and MACRO total number of observed upward events.

6 Discussion

Experiments with atmospheric neutrinos can be ranked in the following order as regards their potential for discovery of new physics:

1. The ratio ν_e/ν_μ. The principal uncertainties in the input to the calculation of this ratio all cancel. Three completely independent calculations [24, 10, 25] agree within 5% of each other for the expected value of this ratio.

2. Angular distributions of neutrino fluxes in a particular energy region. Again, the principal uncertainties cancel in the calculation of the beam, but the statistical significance is poorer because the data must be subdivided into angular bins.

3. The ratio of stopping to throughgoing neutrino-induced upward muons. The cancellation of uncertainties in the calculations here is less complete because the two classes of events in this ratio correspond to different ranges of energy.

4. The absolute intensity of ν_μ or ν_e.

It is noteworthy that the experiments with the greatest statistical significance [6, 8] show a significant deviation from the most secure feature of the atmospheric neutrino beam—the ν_e/ν_μ ratio. The measured value is apparently greater than the ratio at production. The possibility that the discrepancy might result from an oversimplified use of the Fermi Gas Model (FGM) in calculating the neutrino interaction rate is not borne out by careful investigations [26], which conclude that the energy is high enough so that any deviation from the FGM affects both flavors of neutrinos similarly.

If the observed effect is a signal of neutrino oscillations, the lack of observed angular dependence for low energy ($\lesssim$ 1 GeV) events [6, 8] implies $\delta m^2 > 10^{-3}$ eV^2. The large size of the discrepancy requires $\sin^2 2\theta > 0.5$. Much (not all) of available phase space for a $\nu_e \leftrightarrow \nu_\mu$ explanation is ruled out by reactor limits.

In a simple two-flavor oscillation scheme, the oscillation probability for a muon-neutrino is

$$P_{\nu_\mu \to \nu_2} = \sin^2 2\theta \sin^2 \left[1.27\, \delta m^2(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} \right]. \tag{3}$$

A ν_μ disappearance interpretation (e.g. $\nu_\mu \leftrightarrow \nu_\tau$) of the ratio ν_e/ν_μ in low-energy contained events with $\delta m^2 > 10^{-2}$ eV^2 and large mixing angle would imply disappearance of $\sim$ 100 GeV ν_μ with path-lengths $L > R_{Earth}$. This in turn predicts a deficit of ν_μ-induced, upward, throughgoing muons. Measurements of this rate are inconclusive because of uncertainty in the normalization of the calculated neutrino flux. There is also some uncertainty in the neutrino cross section.

Combining all their data (sub-GeV and multi-GeV), the Kamiokande group find a rather limited allowed region, either for $\nu_\mu \leftrightarrow \nu_\tau$ or for $\nu_\mu \leftrightarrow \nu_e$ with nearly full mixing and with $\delta m^2 \sim$ 1 to 2×10^{-2} eV^2. Simultaneous analysis of all atmospheric and solar neutrino data sets (as of 1993) in the space of 3-flavor neutrino oscillations [27] favors oscillation predominantly in the $\nu_\mu \leftrightarrow \nu_\tau$ sector to explain the atmospherics and in the $\nu_\mu \leftrightarrow \nu_e$ sector for the solar neutrinos. This in turn implies a "natural" order for the neutrino masses, but with $m(\nu_\tau) \sim 0.1$ eV, rather than the value of $\sim$ 10 eV expected from a quadratic see-saw starting from $m(\nu_\mu) \sim 0.003$ eV to solve the solar neutrino puzzle.

In the next year, we expect higher statistics from the Soudan experiment and further results from the KEK beam test. After that, SuperKamiokande will contribute to our understanding of atmospheric neutrinos. Confirmation of the atmospheric neutrino deficit as a manifestation of neutrino oscillations may need to await one of the accelerator based long baseline neutrino experiments.

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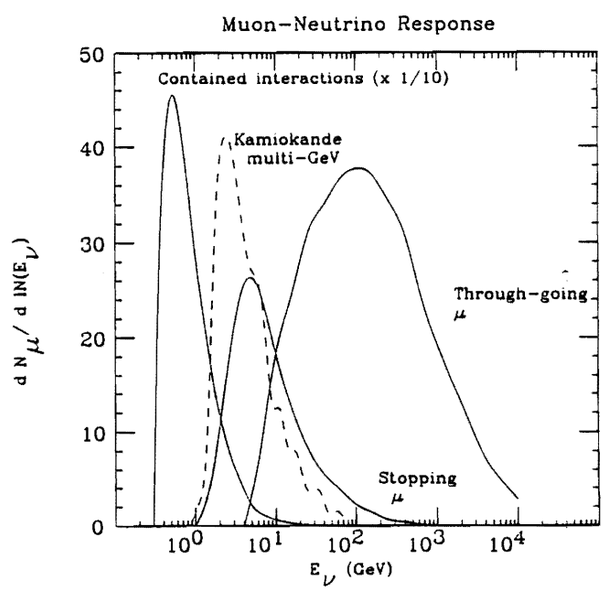
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